

Barrier Island Migration and Morphologic Evolution, Fire Island Inlet, New York

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ABSTRACT

Fire Island Inlet, New York, is an overlapping barrier inlet system where the inlet channel lies on an east-west orientation with Fire Island to the south and east and Cedar Island and Jones Beach to the north and west. The main purpose of this study was to examine the response to inlet stabilization of inlet geomorphology and adjacent shoreline behavior over a time scale of decades. This study quantifies inlet migration, spit extension, and shoreline change in the areas surrounding Fire Island Inlet, describes major long-term influences to the inlet system, and interprets the consequences of engineering operations to the position of neighboring shorelines. The analysis was performed using ESRI Arcview[™] GIS and the BeachTools extension, which was developed specifically for this purpose. The available data to perform this analysis consisted of aerial photography covering the period from 1936 to present, historical shoreline data from the U. S. Coast & Geodetic Survey land surveys dating back to 1834, and topographic data from NOAA hydrographic surveys and recent SHOALS data.

Fire Island Inlet's evolution has been a trend of downdrift erosion and updrift accretion. The addition of a jetty on Fire Island's western tip in 1941 and a sand dike within the inlet in 1959 did not halt this trend. Excess sediment bypasses the jetty and migrates into the inlet area, forming spits and shoals. This deprives the downdrift areas of Oak Beach and Gilgo Beach of sediment.

Currently, dredging costs for Fire Island Inlet are \$5 million per year. If the navigation channel were not regularly maintained, it would close due to shoaling within the inlet. A potentially more cost-effective way to deal with the perpetual inlet shoaling would be to relocate the inlet.

ADDITIONAL KEYWORDS: barrier island morphology, inlet migration, spit formation, sediment transport, littoral drift, regional sediment management, and geographic information systems

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INTRODUCTION

Fire Island Inlet is located on the south shore of Long Island, New York (Figure 1) and provides a navigation channel between the Atlantic Ocean and Great South Bay. The south shore of Long Island is 120 miles of headlands and barrier beaches, breached by six inlets (Panuzio, 1968). The channel is positioned between Oak Beach to the north and the western tip of Fire Island to the south (Kraus *et. al.*, 2003). In its present condition, the inlet has a depth of about 10 to 14 ft at mean low water, a total length of about 3.5 miles, and a width of approximately 3,500 ft (USACE, 2002).

Records show that Fire Island Inlet has existed since the early 1700's (Figure 2) and that Fire Island has undergone considerable extension to the west since the opening of the inlet. The Fire Island Lighthouse, built in 1825, was originally less than 500 ft from the end of the island. Engineering activities began in 1927 around Fire Island Inlet starting with the placement of 40 million cubic yards (cy) of embankment fill to create an Ocean Parkway from Jones Inlet to Captree State Park (Figure 3). By 1940, Fire Island had extended such that the terminus of Democrat Point was 5 miles west of the lighthouse (Gofseyeff, 1952). To halt the rapid westward migration of Fire Island, a 5,000-ft jetty was constructed at Democrat Point in 1941 by the USACE (Figure 4).

According to the analysis of the photographic record, the sand trapping capacity of the jetty was reached by 1948. The sand then swept around the edge of the jetty and accumulated as spits and shoals within the channel as Gilgo Beach and Oak Beach eroded from the lack of sediment supply. By 1956, the spit extended about one mile northwest of the jetty and constricted the inlet width to 1,200 ft. In 1959, to reduce the extensive erosion around Oak Beach, a one-half mile perpendicular dike (known locally as “The Sore Thumb”) was created from approximately 1.1 million cy of material dredged from the ebb shoal (Figure 5). The dike was to some extent advantageous in preserving channel location and preventing erosion on the downdrift end of the inlet. However, the channel still requires almost yearly maintenance dredging to maintain navigational channel depths (USACE 2002).

The total volume of material that has been dredged from Fire Island Inlet channel since 1946 is approximately 19 million cy (Table 1). The cost has been about \$5 million per year to dredge the inlet and bypass the sand to downdrift locations. This cost is equivalent to the combined annual dredging operations performed on the other five tidal inlets on the south shore of Long Island (Kraus *et al.*, 2003).

INLET DYNAMICS

Inlets evolve toward dynamic equilibrium, and thus continuously respond to waves, littoral drift, and engineering activities. The stability of an inlet is dependent upon a balance between currents that carry sediment into the inlet channel from the wave-dominated littoral system, and the strong tidal flows that scour the channel (Headland *et al.* 1999). Inlets can abruptly shoal due to rapid deposition of littoral sand during storm events. Over time, the main channel of an inlet can split into multiple channels by natural or anthropogenic causes, be impacted by changes in the lagoon/bay area surrounding the inlet, or experience lengthening of the inlet conveyance channel (Bruun, 1978).

Damping of tidal currents by increased friction as Fire Island Inlet channel lengthened over the past 70 years, is the main reason for the excessive shoaling

in some areas of the inlet. Other areas of the inlet system have been subjected to excessive scour due to migration of tidal channels around areas of shoal buildup.

Numerous barrier island breaches have occurred along the south shore of Long Island due to major storms. Breaches are usually short-lived because they tend to shoal and close or they are closed by mechanical operations. Moriches and Shinnecock Inlets were originally opened by storms in 1931 and 1938. Jetties now stabilize both of these inlets (Headland *et al.*, 1999).

Sea level rise is known to increase the height of wave run-up onto beaches and contribute to beach erosion. This increase in water depth alters the equilibrium beach profile, leading to shoreline retreat and increasing the possibility of coastal disasters. When integrated over the long term, sea-level rise combined with episodic storm surge can have a severe effect on coastal areas. The combined effects of eustatic (worldwide) sea-level rise and isostatic adjustments in the Long Island area land elevations have resulted in a net relative sea level rise of about 1 ft over the past 130 years. Tide gauge records indicate that there has been an 0.36 ft per century eustatic rise in sea level (Dean and Dalrymple, 2002; Gornitz *et al.*, 1982).

The currents and tidal prism of Fire Island Inlet have had a remarkable effect on the transport of longshore sediment since the 1950's. In the 1950's, the average current speed in the inlet was about 5 ft/s and the mean tidal range was approximately 4.1 ft at the entrance and 0.7 ft in Great South Bay (Gofseyeff, 1952). This yields a tidal prism of 1.1×10^8 cy for Fire Island Inlet (Kraus, *et al.* 2003). The net longshore sediment transport is directed to the east and has been estimated to be in the range of 230,000 cy to 600,000 cy per year depending on calculation methods and assumptions made to estimate the long-term littoral sand budget (Rosati *et al.*, 1999). The jetty directs this littoral drift into the inlet area, resulting in rapid shoaling and extension of Democrat Point (USACE, 2002).

Tidal inlets are often considered from an equilibrium point of view (Bruun, 1978; Escoffier, 1977). According to the Escoffier stability criteria, Fire Island

Inlet is marginally stable, which is indicated by a constant relative position of the inlet cross-sectional areas relative to pertinent closure curves in the Escoffier relation (Headland *et al.*, 1999). There is a considerable amount of sediment entering Fire Island Inlet each year through littoral transport and the excessive length of the inlet channel makes it hydraulically inefficient.

METHODS

An ESRI Arcviewtm extension, known as BeachTools (Hoeke, *et al.* 2001), was developed to identify and quantitatively establish the position of the shoreline and other coastal features from aerial imagery. The extension uses image analysis techniques to extract a polygon representation known as a shoreline shapefile to map the beach between the vegetation line and the wet/dry line (saturation line). The BeachTools extension also calculates transects from a user-defined baseline at selected intervals, allowing for high frequency, shore-perpendicular measurements of the wet/dry and vegetation lines. Differencing the transect lines from various aerial survey sets provide quantitative estimates of erosion and accretion of the beach between the lines.

The project methodology included shoreline extraction from a database of aerial photography and the creation of gridded topographic surfaces from 1933 and 1950-1951 hydrographic surveys and the May 1996 Scanning Hydrographic Operational Airborne Lidar Survey or SHOALS data (Irish *et al.*, 2000). The vertical accuracy is ± 6 in for the hydrographic survey data, and ± 10 in for the SHOALS data. Horizontal accuracy for both types of surveys is expected to be on the order of ± 10 to 20 ft. From these datasets, volume and spatial change calculations were performed.

ANALYSES

Morphologic evolution and engineering over the past 70 years

The Fire Island Inlet system includes a 17-mi span of barrier islands and water, stretching from the town of Gilgo Beach on Jones Beach-Cedar Beach Barrier Island to the village of Saltaire on Fire Island. The aerial photography

portion of the analysis used photographs from the following years: 1940, 1983, 1988, 1995, and 2000. The 1940 data set served as the beginning point for comparisons with later aerial survey dates. Figure 6 compares the configuration of barrier island morphology near Fire Island Inlet between 1940 and 2000. Due to construction of the Democrat Point Jetty, construction of the sand dike and extensive dredging of inlet shoals the entrance to the inlet entrance has shifted south by approximately 1,600 ft and narrowed by 200 ft (Figure 6).

Prior to 1939, Democrat Point was rapidly migrating westward, Fire Island Inlet channel was lengthening, and Oak Beach to the north and the east end of Cedar Beach were under erosion pressure from strong tidal currents within the inlet-barrier overlap area (Figure 4). However the west end of Cedar Beach and Gilgo Beach to the west of the inlet were wide and not directly impacted by erosion by tidal currents of the overlap zone.

Jetty construction at Democrat Point began in June 1939 and was completed in April 1941 (Gofseyeff, 1952). The jetty halted the westward migration of Fire Island, but soon excess sand began washing around the tip of the jetty. Spit formation began to occur on the western side of the jetty and Oak Beach and downdrift areas began to erode at a greater rate than before jetty placement. The sand dike constructed in 1959 was designed to divert strong tidal currents away from Oak Beach. As early as January 1960, Cedar Beach began to experience build-up of sediment around the dike. During the 1960's, the dike was able to capture some of the sediments that had accumulated around the jetty and sediment began to fill in a zone extending approximately 10,000 ft to the west of the dike. During the 1970's and 1980's, shoaling around the dike area continued, and it became evident that the shoal near the dike had begun to align itself with the rest of the shoreline. However, the massive spit accretion in the vicinity of Democrat Point Jetty and trapping of sand within the inlet shoal system had become a considerable problem for navigation and sand bypassing to Cedar Beach and Gilgo Beach to the west.

Since the 1960's, the sediment-starved downdrift areas of Cedar and Gilgo Beach have been maintained by a combination of sand buildup around the

dike and a series of fill projects conducted with sand dredged to keep the Fire Island Inlet navigation channel open (Table 1). However, problems related to spit formation at Democrat Point, shoaling within the inlet, and downdrift erosion continue, requiring responses with dredged material placement.

Longer-Term Morphologic Evolution and Shoal Volume Changes

Historic records indicate that Fire Island has migrated westward since construction of the Lighthouse in 1827. Analysis by Leatherman and Allen (1985) and Liu and Zarillo (1987) indicate that the westward migration of the modern Fire Island Inlet is part of a much longer-term evolution of Fire Island that includes reworking of the barrier system by several episodes of inlet breaching and migration. The 1835 configuration of Fire Island Inlet shows a small inlet to the west of what is now Captree Island and possibly the development of the modern-day Oak Island as a flood shoal. Geomorphic details from the remainder of the 19th century USC&GS T-sheets are incomplete, but the 1909 configuration shows Cedar Beach to Oak Beach area as a fully integrated barrier system (Figure 7). Over the longer term, it is likely that Oak Island, Cedar Island, Captree Island, and possibly other small islands, such as the Fire Islands to the east in Great South Bay, were originally formed as flood shoals as inlets in the vicinity opened and closed and Fire Island extended to the west.

The 1924 configuration shows a small inlet to the northwest of Fire Island Inlet and the continued westward extension of Fire Island that overlapped the Oak Beach area to the north (Figure 8). In 1924, the Fire Island Inlet cross-section was apparently near equilibrium, but from 1924 to 1937, the inlet cross-section decreased (Headland, *et al.* 1999). By 1937, the inlet had nearly shoaled to the point of closure. From 1937 to about 1940 the inlet began to scour and increase in depth and cross-section. Upon completion of the Democrat Point Jetty in 1941, sediment transport across the inlet channel decreased. By 1950, the jetty's compartment was full and sand began bypassing the jetty and constricting the channel. Since then the inlet again shoaled to near closure (Figure 5) as the Democrat Point Jetty bypassed large volumes of sand. The

inlet has been maintained by extensive dredging and other engineering activities to keep it open for navigation (Headland et al. 1999).

Volume calculations of the Fire Island Inlet shoal features were based U. S. Coast & Geodetic Survey bathymetric information from 1933 and 1950 available in digital format and from the 1996 SHOALS data. The cut and fill areas based on a comparison of 1933 and 1996 surveys are shown in Figure 9. Fire Island Inlet includes a large submerged ebb shoal system to the west of the inlet entrance, and a main flood shoal to the east of the barrier overlap area. A feature termed a secondary flood shoal is located within the inlet channel to the south of Oak Beach.

Volume calculations indicate that the ebb shoal volume increased by 11.8 million cy between 1933 and 1996 (Figure 10). The majority of this increase occurred between 1933 and 1950 when approximately 10 million cy of sand was added to the ebb shoal (Figure 10). Over time, the entrance to Fire Island Inlet has become increasingly filled with sediment, making navigation within the channel difficult. In 1996, the ebb shoal volume was calculated at over 32 million cy of sediment, enough to supply the western beaches with about a century's worth of sand. The ebb shoal sediment volume did not dramatically increase from 1950 to 1996, which may be explained by an increase in the occurrence of storms within the area during that time and mining of approximately 5 million cy of sand from the ebb shoal for nourishment of downdrift beaches (Figure 11, Table 1).

The main flood shoal system to the east of the barrier overlap area increased in volume by 3 million cy from 1933 to 1996. The primary flood shoal does not contain as much sediment as the ebb shoal and was estimated in 1996 to contain approximately about 21.3 million cy of sand above a base elevation of -29.5 ft NGVD. The flood shoal is also partially intertidal having elevations that exceed mean low water along the rim of the fan-shaped subunits that form the overall feature. Navigation through the inlet channel is somewhat restricted to the south of Oak Beach due to the presence of the secondary flood shoal accumulation within the inlet interior of the inlet. There has been little cutting or

erosion of the main or secondary flood shoal versus the amount of filling or deposition that has taken place (Figure 12, 13). This may be explained by the lack of dredging of the flood shoals for beach fill and sand bypassing. The volume of the secondary flood shoal, calculated from a base elevation of -37.7 ft NGVD, was estimated to contain about 15.2 million cy of sand in 1996.

The combined volume of the main and secondary flood shoals is approximately 36.5 million cy, versus 32.1 million cy for the ebb shoal. A factor that might have contributed to the relatively slow growth of the ebb shoal over the past 50 years is the persistent dredging and bypassing of sand from the navigational channels, which might otherwise feed the growth of the Fire Island Inlet shoals. In addition to channel dredging and sand bypassing directly from the ebb shoal, the capture of sand in the main and secondary flood shoal is another factor slowing the growth of the ebb shoal over the last 50 years.

CONCLUSIONS

The stability and morphology of an inlet are dependent upon a balance among currents that carry sediment into the inlet channel, tidal flows within the channel that scour the banks and channels, and wave-driven currents that provide littoral sediment supply and sand bypassing. Engineering structures and sand management practices interact with natural processes to define the morphologic condition of an inlet. In the case of Fire Island Inlet, a strong westward-directed net littoral sand transport past the Democrat Point Jetty is a dominant process for the evolution of the inlet and surrounding barrier segments. The Escoffier (1977) closure curve identifies Fire Island Inlet as being marginally stable. The excessive length of the inlet channel through the barrier overlap area makes Fire Island Inlet hydraulically inefficient. Without continued dredging operations, Fire Island Inlet would likely close and, in fact, seemed to be near closure in 1940 and again in 1950 due to excessive shoaling.

The addition of a jetty on Fire Island's western tip in 1941 impounded littoral sand and halted the westward extension of the barrier island, but may

have accentuated beach erosion in the downdrift areas. Excess sediment moving around the jetty and migrating into the inlet area forming spits and shoals does not bypass the inlet and thus reduces the supply of sediment to Gilgo Beach. The sand dike constructed in 1959 slowed, but did not halt this trend. Buildup of the secondary flood shoal in the barrier overlap area may have also contributed to erosion problems along Oak Beach by impounding sand and promoting strong currents in the constricted tidal channel around the shoal.

The overlapped barrier configuration of Fire Island Inlet distributes shoaling and erosion patterns over a wide region. The configuration requires navigational dredging and sand management activities to include a much larger area compared to more common inlet configurations. Thus, the review of historical data and analysis presented here is in agreement with a hypothetical discussion of relocating Fire Island Inlet to the east in a more north-south alignment (Kraus *et al.*, 2003). This configuration would have a shorter, more hydraulically efficient inlet throat section and a more confined and manageable redistribution of sediment along adjacent beaches.

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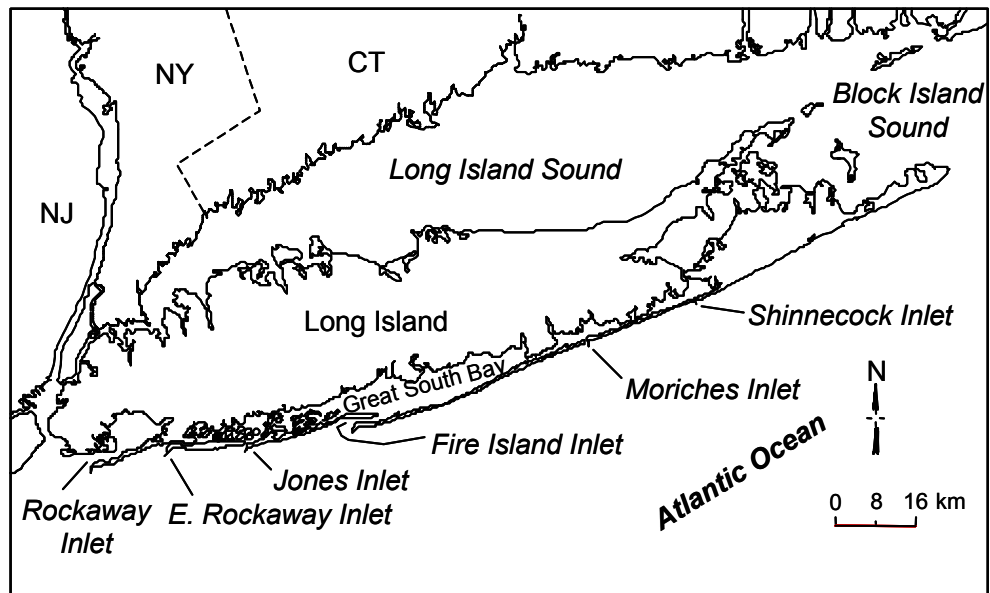


Figure 1. Location of Fire Island Inlet, Long Island, New York. (Kraus et al. 2003).

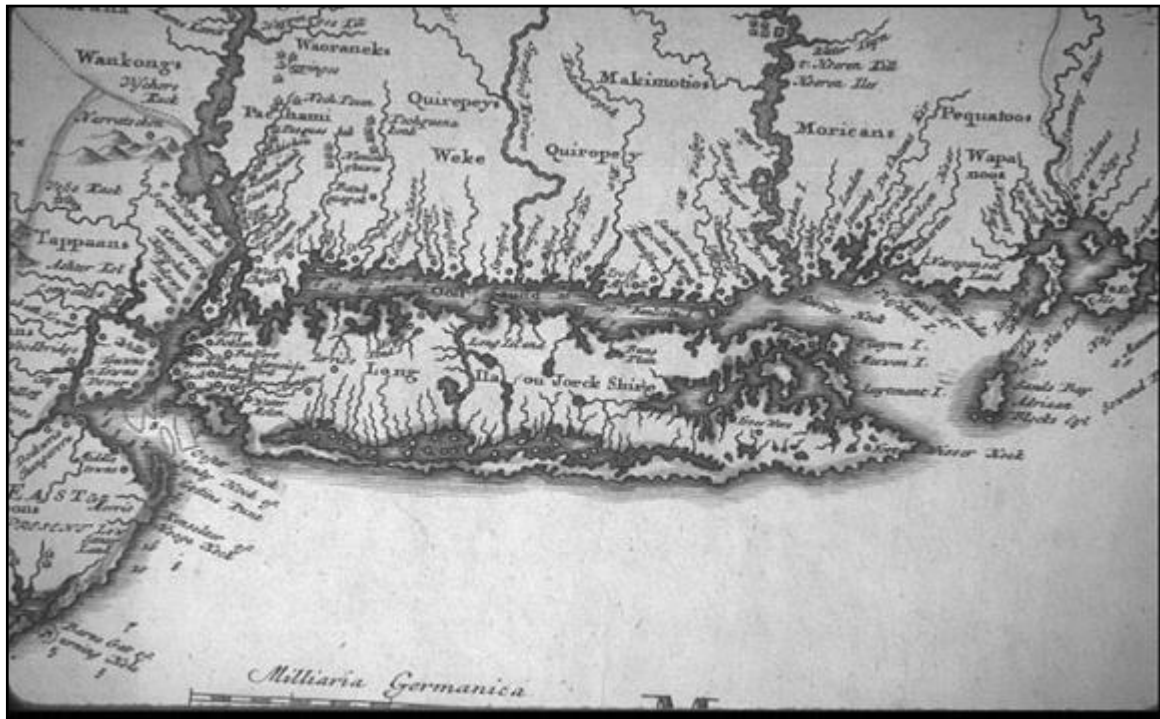


Figure 2. Johann Baptista Homann shows inlets along the south shore of Long Island in *New England in North America*, 1724. (Courtesy of New York State Library, Manuscripts and Special Collections).

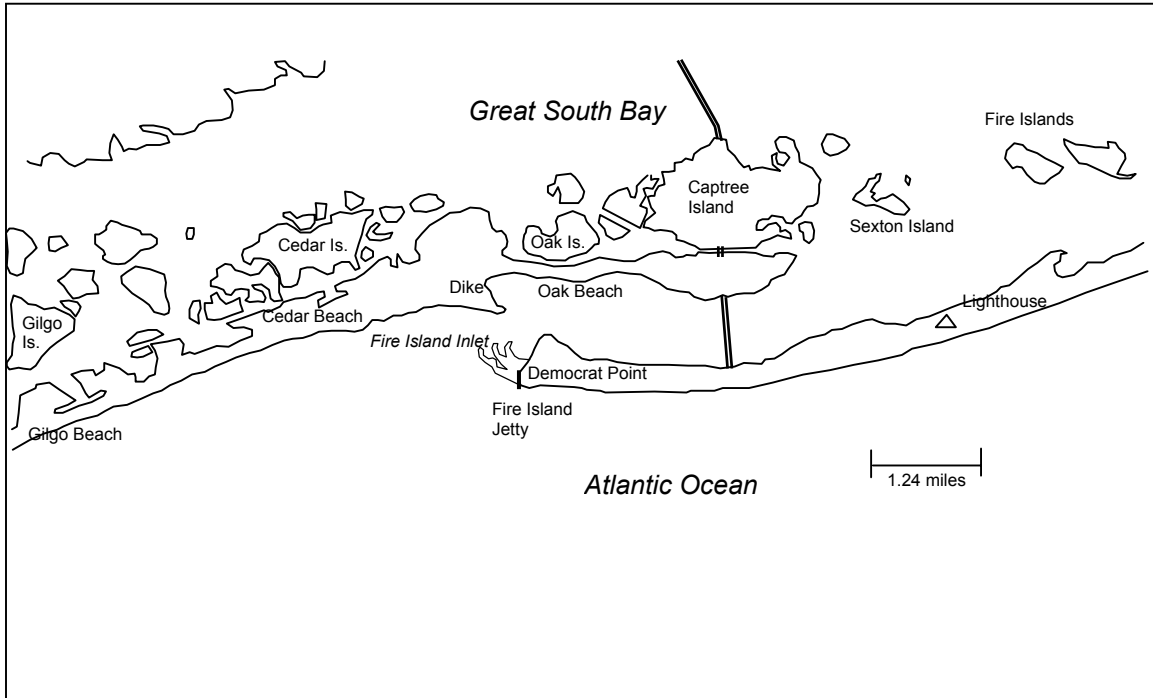


Figure 3. Location map for Fire Island Inlet

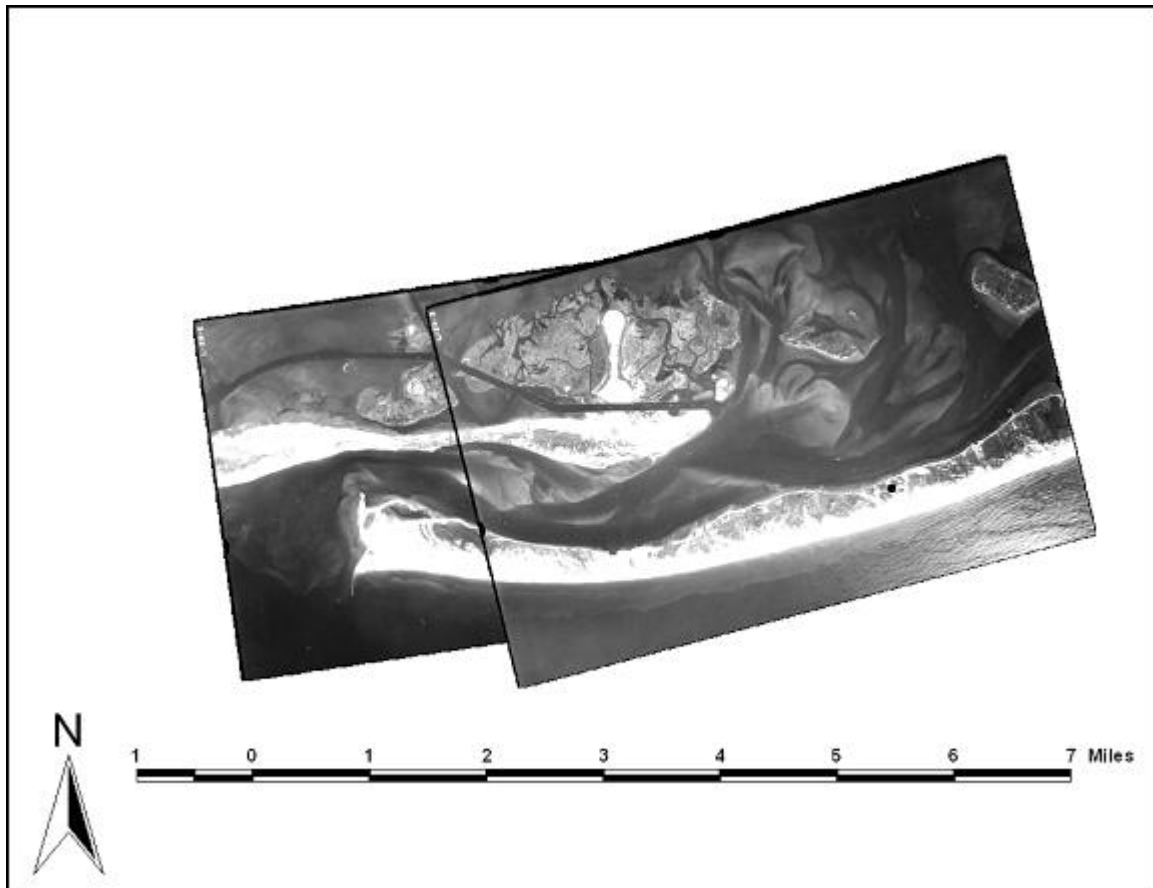


Figure 4. Construction of the rubble mound jetty off Democrat Point began on May 23, 1939 and was completed on April 15, 1941 (Gofseyeff 1952).

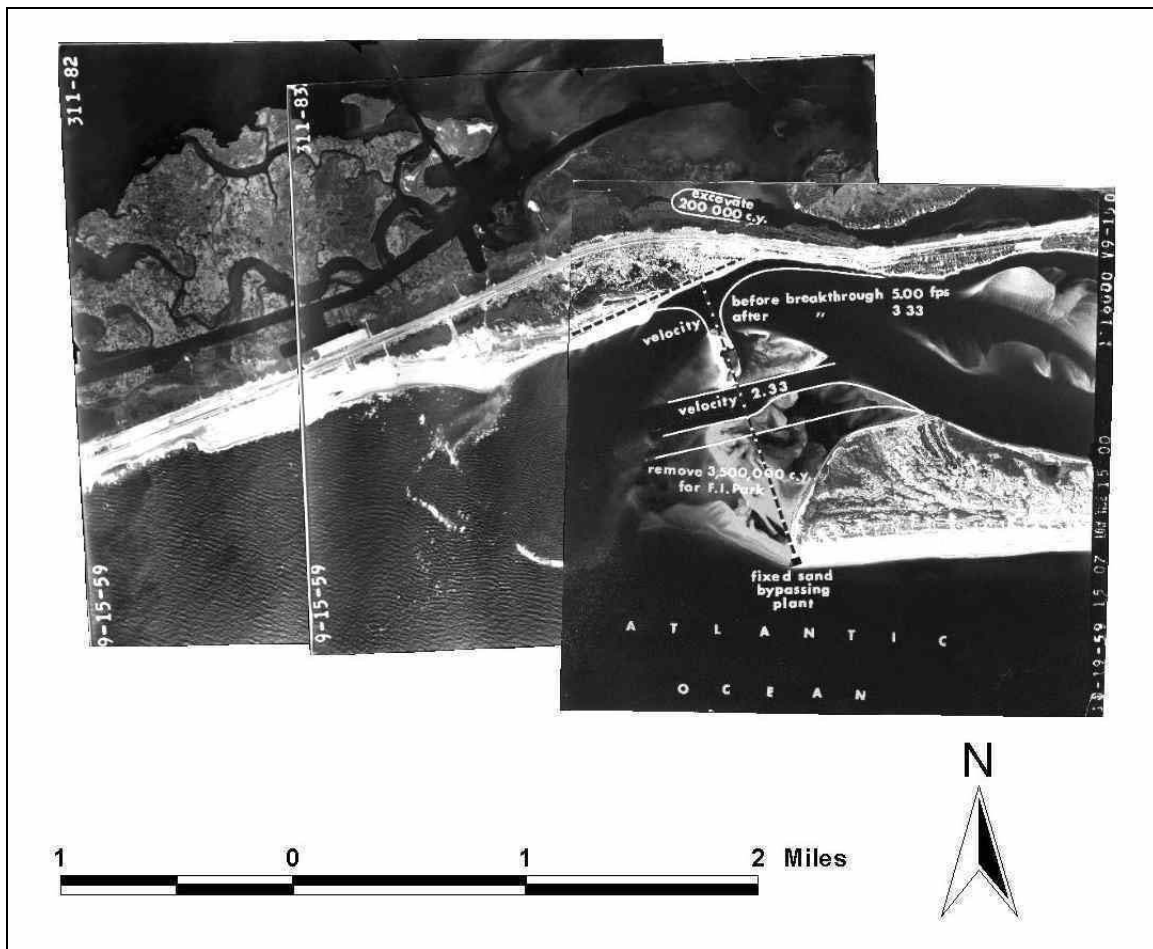


Figure 5. Sand dike was created in 1959, to divert currents that caused heavy erosion focused on north side of inlet (Panuzio 1968).

Table 1. Fire Island Inlet engineering activities (USACE-NAN (1998), USACE-NAN (1985), CENAN Records (1998-2002). Adapted from: USACE (2002)			
Date	Activity	Description	Location
1927	Ocean Parkway	40 million cubic yards of embankment fill	Fire Island Inlet to Jones Inlet
1941	Jetty	5,000-ft stone jetty to halt Inlet migration	Eastern Bank
1946	Dredging & Beach fill	Channel dredged to 15 ft deep and 200 ft wide; 400,000 cubic yards from channel placed on 4,000-ft segment of Oak Beach	Inlet and Oak Beach
1946 - 55	Beach fill	Nourishment averaged 150,000 cy/year	Oak Beach
1950	Design	Authorized channel dimensions modified to 10 ft deep & 250 ft wide	Inlet
1953	Storm	Storm results in new channel dimensions as modified in 1950	Inlet
1954	Dredging	Maintenance dredging 118,000 cubic yards	Inlet Channel
1955	Dredging	Advanced dredging to preclude northward channel shift	Inlet
1955-59	Beach fill	1,000,000 cubic yards along eastern segment of Fire Island to Jones Inlet reach	Gilgo & Tobay Beaches
1956-59	Dredging	Maintenance dredging 290,000 cubic yards	Inlet Channel
1959	Dredging & Beach fill	3,100,000 cubic yards dredged from the ebb shoal: 2,000,000 cubic yards placed on feeder beach west of Inlet 1,100,000 cubic yards to construct one-half mile closure dike across channel along Oak Beach; referred to as the Thumb; later fortified with riprap	Ebb Shoal
1960-61	Dredging	Maintenance dredging 292,000 cubic yards	Inlet Channel
1961	Dredging & Beach fill	2,200,000 cubic yards dredged from Bay to protect Ocean Parkway	Gilgo & Tobay Beaches
1963-67	Dredging	Maintenance dredging 747,000 cubic yards	Inlet Channel
1964	Dredging & Beach fill	1,925,000 cubic yards dredged from ebb shoal, placed on feeder beach	Ebb Shoal
1967	Dredging	Material excavated to bolster revetted sand dike	Inlet & Thumb
1968	Dredging	Maintenance dredging 194,000 cubic yards placed at Cedar Beach	Inlet Channel
1968-69	Dredging & Beach fill	Dredged from north of Gilgo Beach and placed on beach east of Gilgo Pavilion	Gilgo
1969-71	Dredging	Maintenance dredging 1,237,000 cubic yards	Inlet Channel
1972-76	Dredging	Maintenance dredging 5,005,000 cubic yards	Inlet Channel
1985-87	Dredging	Maintenance dredging 1,151,000 cubic yards	Inlet Channel
1988-93	Dredging	Maintenance dredging 4,398,000 cubic yards placed at Gilgo Beach	Inlet Channel
1993	Dredging & Beach fill	Placement fronting traffic circle at Robert Moses	Flood Shoal
1994-Mar 2002	Dredging	Dredging 5,180,363 cubic yards: 4,317,250 placed at Gilgo Beach and 863,113 at Robert Moses SP	Inlet Channel

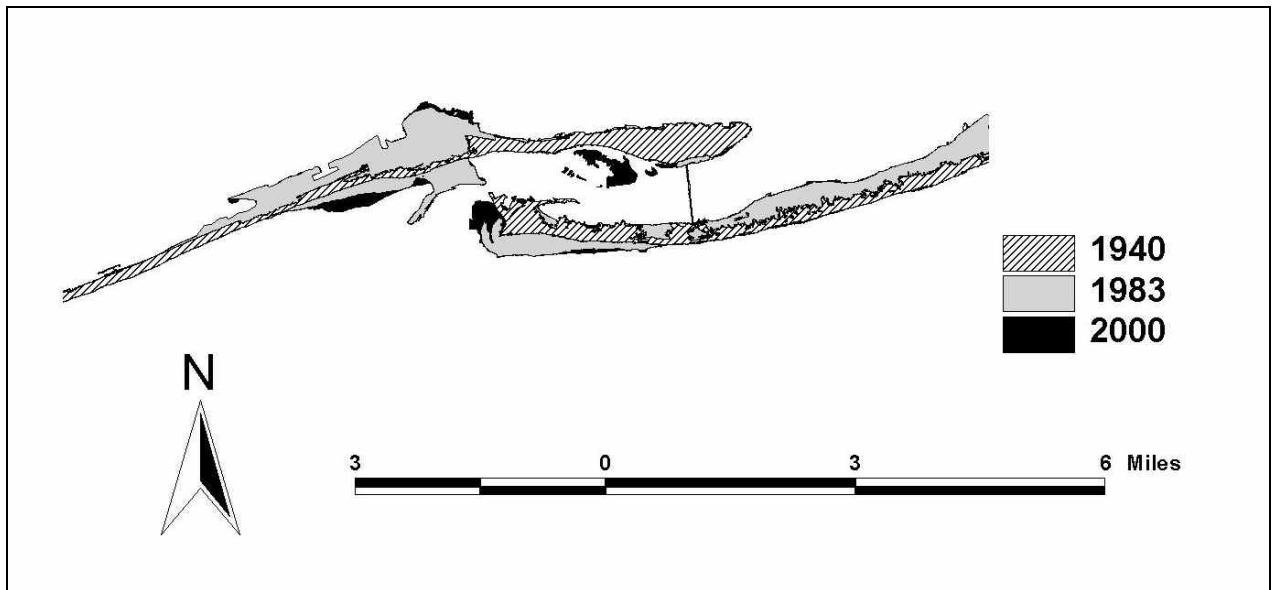


Figure 6. Barrier Island morphology changes in response to engineering activities at Fire Island Inlet between 1940 and 2000.

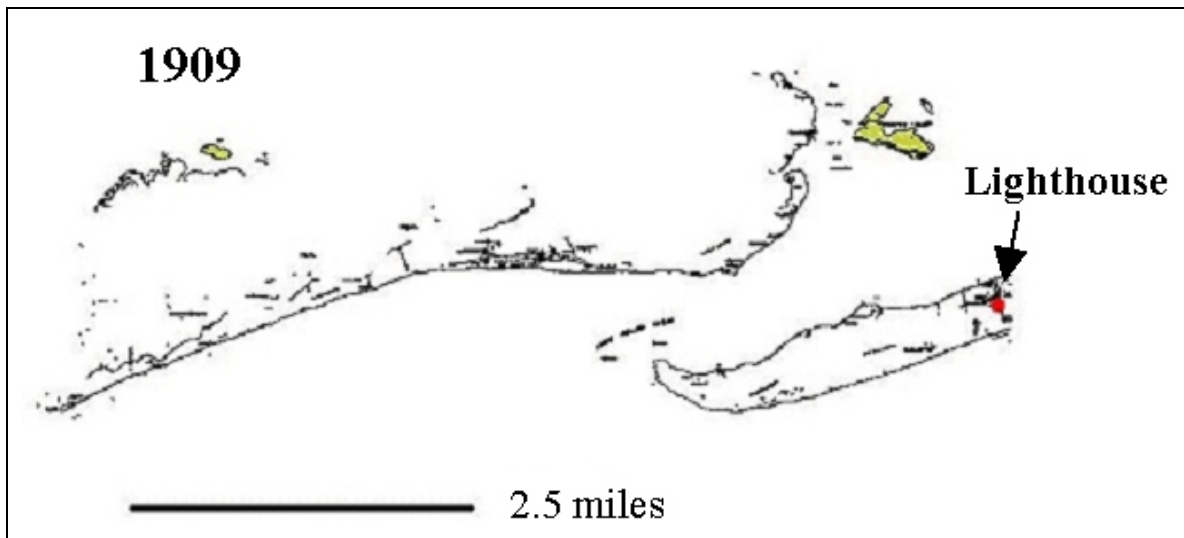


Figure 7. Fire Island Inlet Configuration in 1909.

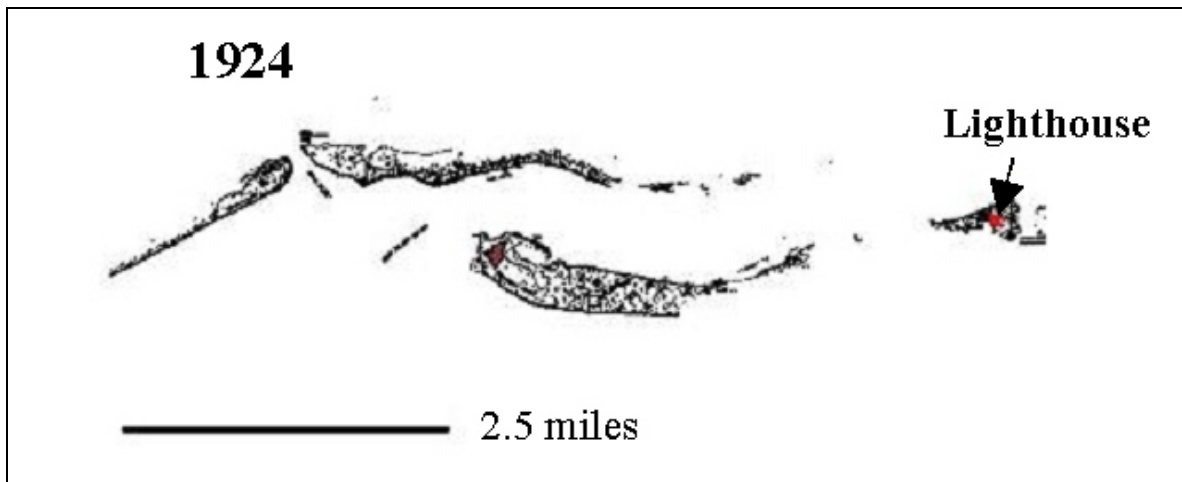


Figure 8. Fire Island Inlet Configuration in 1924.

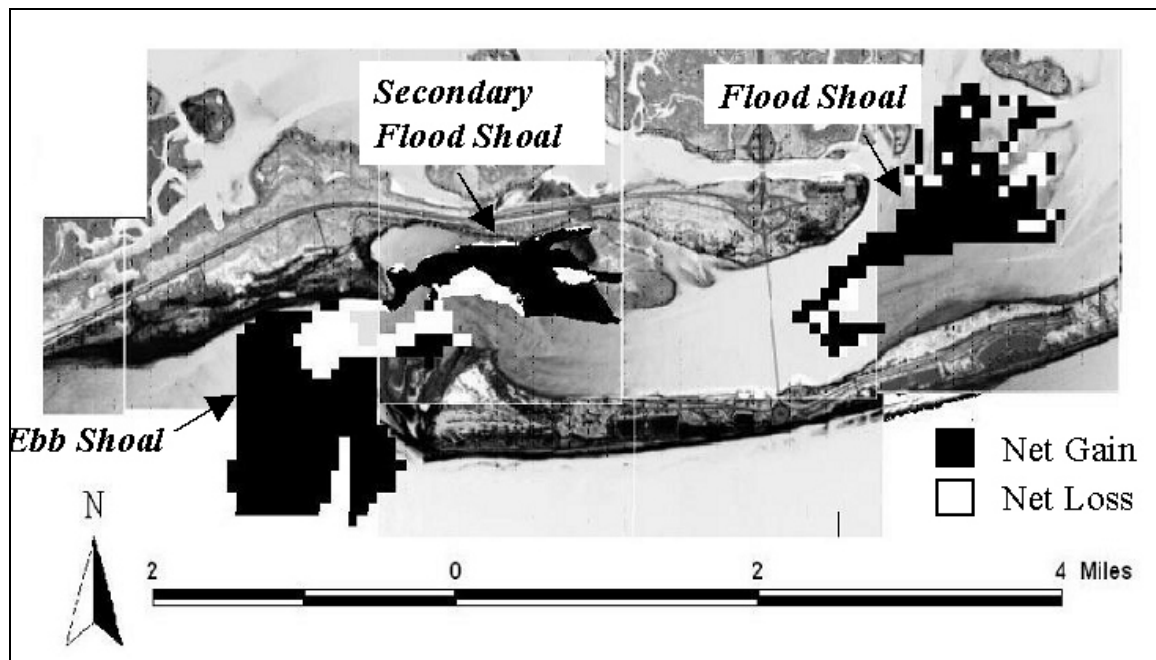


Figure 9. Distribution of net volume gain and loss from Fire Island Inlet shoals based on comparison of 1933 and 1996 bathymetric surveys.

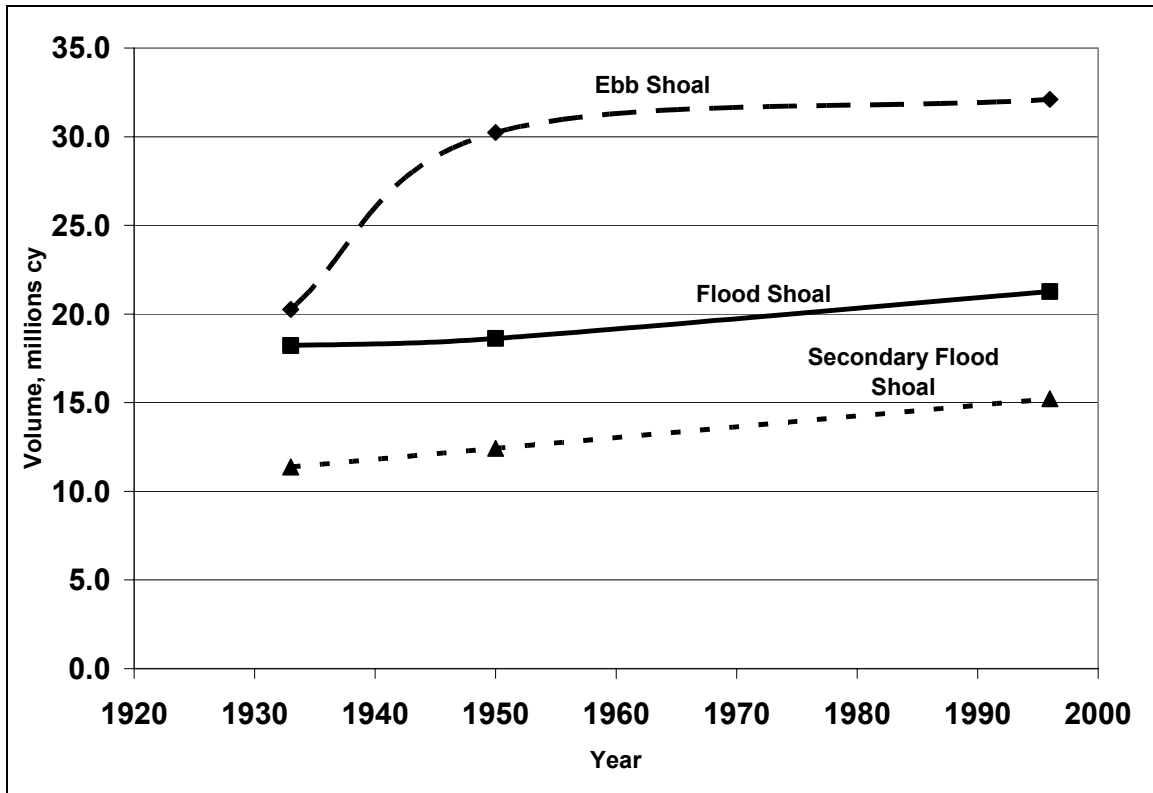


Figure 10. Volume calculations of the flood and ebb shoal within Fire Island Inlet.

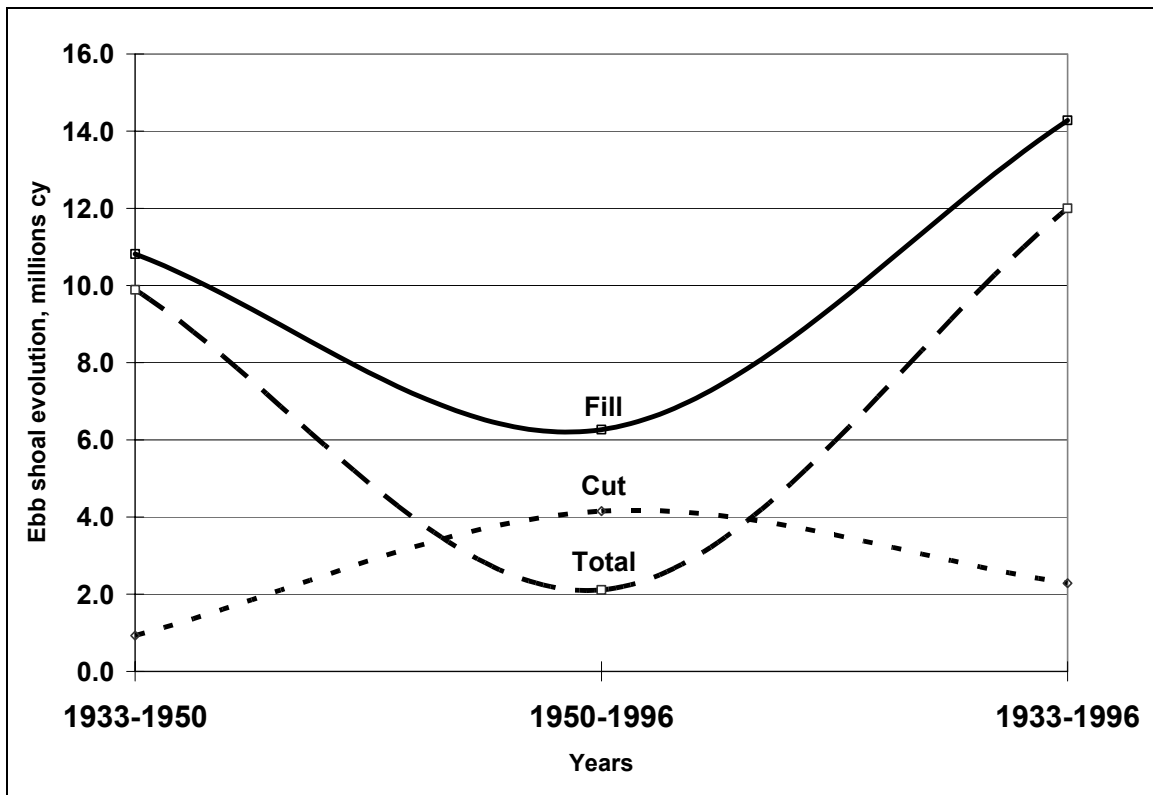


Figure 11. Cut-Fill differences for the ebb shoal from 1933 to 1996.

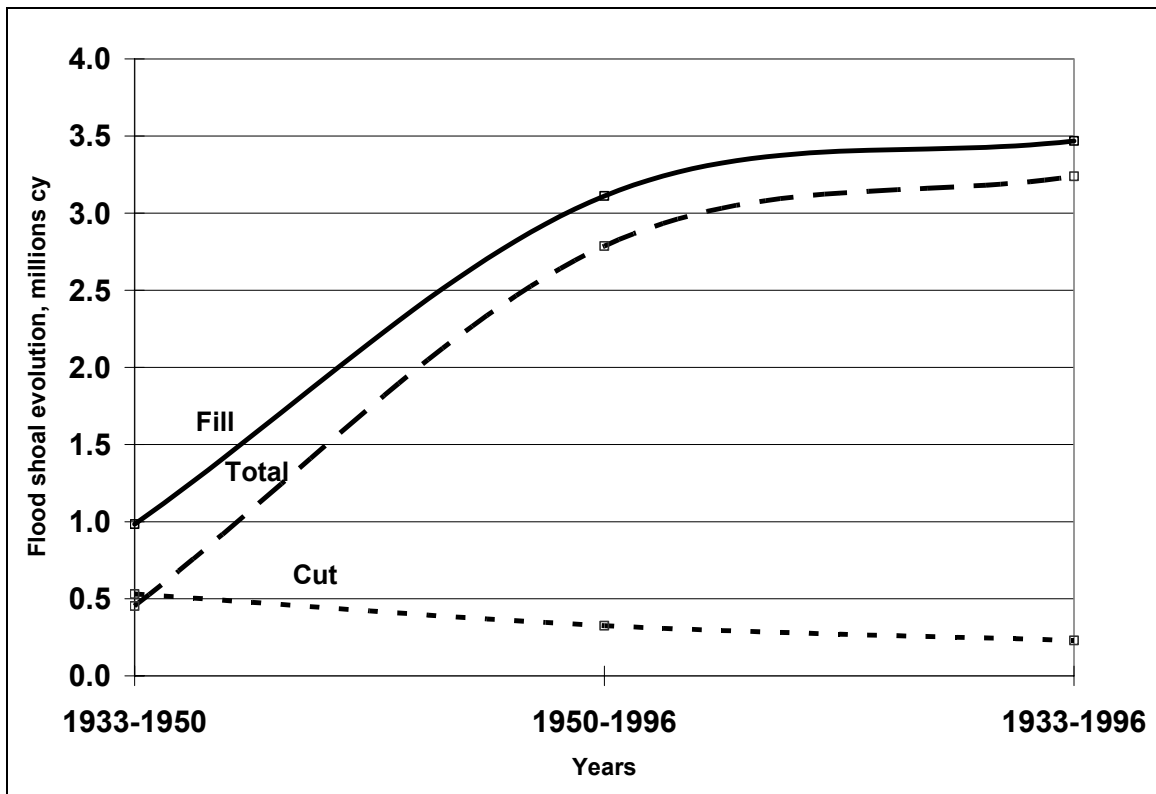


Figure 12. Cut-Fill differences for the primary flood shoal from 1933 to 1996.

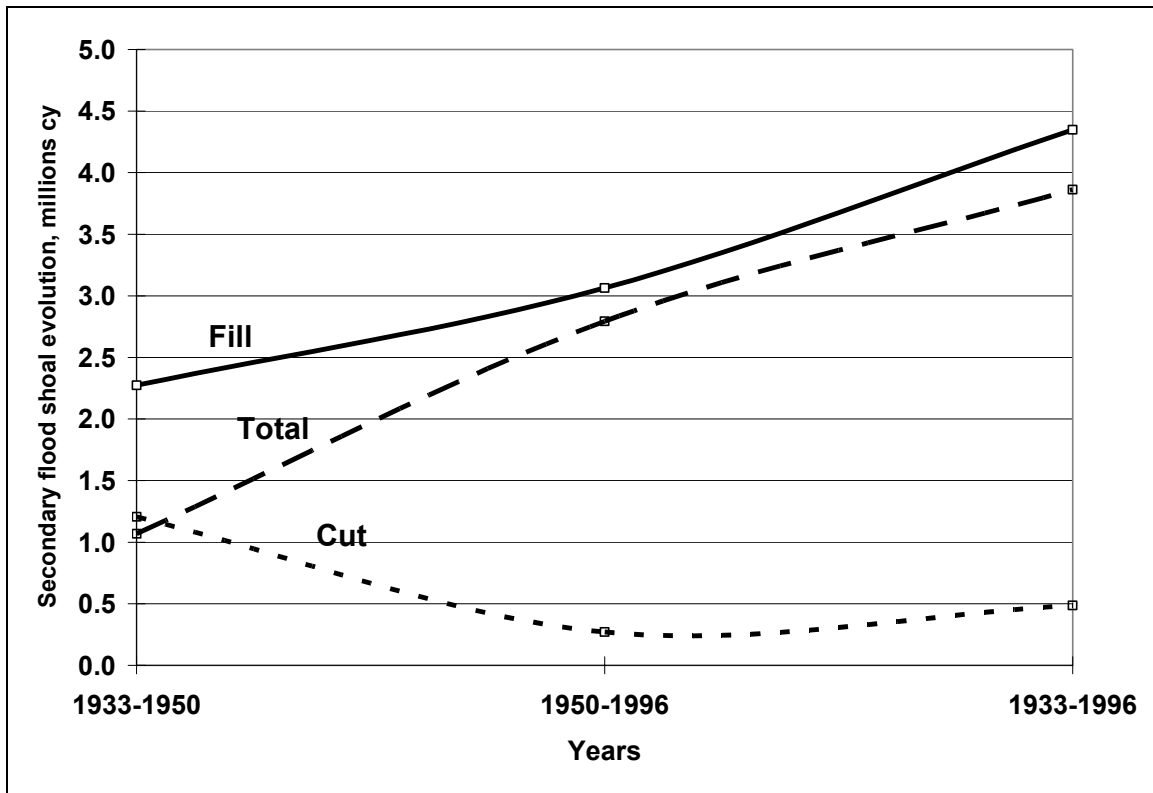


Figure 13. Cut-Fill differences for the secondary flood shoal from 1933 to 1996.